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14. ABSTRACT
The objective of the proposed work was to demonstrate that digital switching of the exchange interaction by real space electron transfer will provide a viable method for accurate control of inter-qubit interactions. In order to fix the strength of the exchange interaction at the fabrication stage we proposed a new technology for 3D confinement of electrons by abrupt epitaxial Si/SiGe interface. During the course of the project we developed CVD growth of high mobility 2D electron gases in Si/SiGe, low damage nanofabrication techniques, in situ cleaning and conformal

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Digital Control of Exchange Interaction in a Spin-based Silicon Quantum Computer

Final Progress Report - period 18 July 2005 – 17 February 2009

Principal Investigators: Leonid Rokhinson, Purdue University, James Sturm, Princeton University

Statement of the problem:

With successful demonstration of single qubit and exchange swap operations in semiconductor qubits during the last few years we need to addresses a few critical obstacles that lie between isolated devices and real systems with many qubits. There are three general areas of concern: (i) How will a scalable architecture maps on the physical devices and their interconnection be allowed by the technology? (ii) Is the process technology capable of making many identical functioning devices at once? (iii) Are the devices capable of a sufficiently low error rate (e.g. $< 10^{-5}$) to be useful for systems? In this project we propose an easily scalable architecture which addresses major sources of errors and decoherence. An analog electrostatic control of exchange interaction is replaced by digital switching of exchange interaction, which will eliminate exponential dependence of exchange on the control voltages. In the proposed structure a qubit consists of a storage quantum dot with an electron spin holding the information. For double qubit (swap) operation electrons from two neighboring storage dots are transferred into a double-dot dimer with lithographically predefined inter-dot coupling. The exchange is controlled by the time the electrons spend inside the dimer before being separated back into the storage dots. This "flying qubit" concept should reduce errors related to the analog control of exchange interactions and is straightforward to scale. We also propose a new "clean" epitaxial Si/SiGe technology, which will eliminate interface traps associated with Si/SiO_2 or Si/air interfaces which usually obscure the transport in nanoscale Si devices. The technology should provide strong 3D confinement, which is a more stringent requirement in Si compared to GaAs due to heavier effective electron mass and, thus, reduced level spacing for the same strength of confining potential.

Summary of the most important results:

a) **CVD growth of 2D electron gas in strained Si**: 2D gas with mobility 10,000 Vs/cm^2 at 0.3 K has been demonstrated. Clear Shubnikov-de Haas oscillations are observed at B>1.5T at 0.3K.
b) **2D electron gas with mobility 300,000 cm2/Vs, density 3 10^{11} cm^{-2}**: we collaborate with Ya-Hong Xie from UCLA and now have access to high mobility MBE-grown heterostructures. We identified that UCLA use the same As-rich substrates from Amberwave we found to produce substantial leakage at low temperatures in last year's work. A specially designed low P-doped wafers will be used for further growth.
c) **Double QW structures with coupled wells** have been grown at Princeton and investigated. We measured electron transfer between the well as a function of electrostatic gate and see clear evidence of inter-layer coupling between the wells.
d) **Ultra-low leakage top-gate Schottky barriers for charge balancing in DQW** has been developed with leakage in tenths of pA range.
e) **DQW with symmetric double-side doping** has been grown at UCLA, detailed investigation has been lingered by the leaking substrate used. New growth is scheduled for mid Sept.
f) **Overgrowth technology with low side gate leakage** across the ovegrowth region, with leakage in tenths of pA range. The overgrowth has no substantial effect on mobility or density of either CVD or MBE 2-D gas structures.

g) **demonstration of epitaxial regrowth with SiGe**. TEM images of low-temperature SiGe regrowth on Si show flat interface with no visible defects.
h) **modeling of 3D quantum dots.** Atomistic modeling of strained 3D Si dot is performed as a function of dot and buffer sizes and buffer composition. Both wavefunctions and energy levels are calculated, valley and level splitting are analyzed.

Technological progress:

a) **Conformal SiGe re-growth**: We achieved conformal epitaxial re-growth with no structural defects as confirmed by TEM, see Fig. 1. We also demonstrate that re-growth does not lead to the degradation of 2D gas quality.

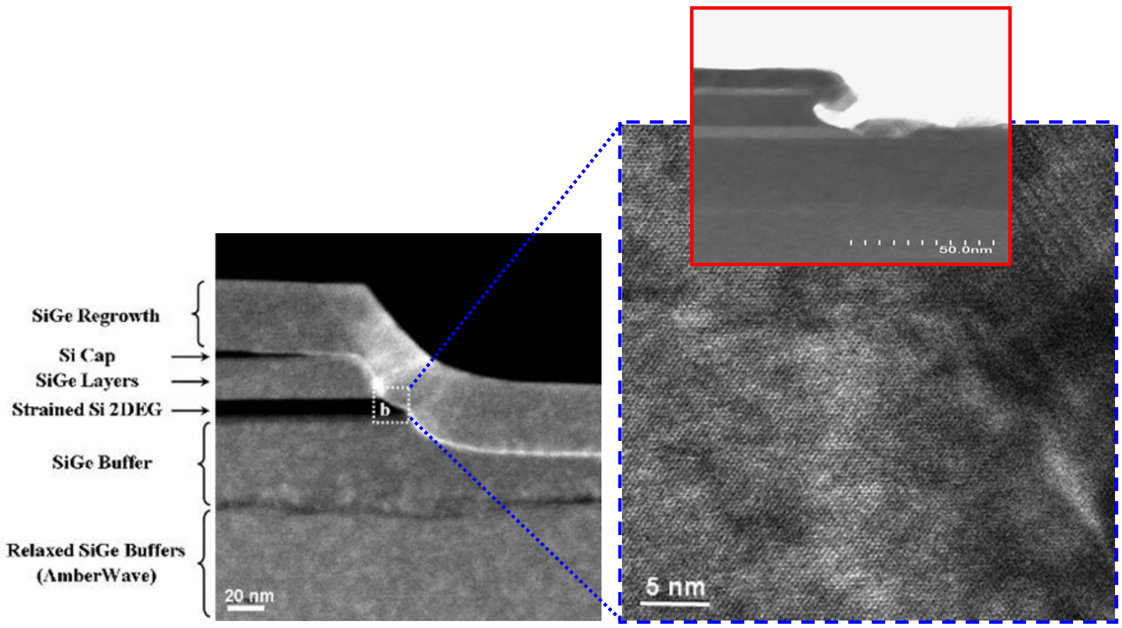

Fig. 1. TEM micrograph of and edge after SiGe regrowth. In the red inset we show an example of non-conformal regrowth from previous years.

b) Effect of Substrate Doping on Leakage. We identified that As diffusion is greatly enhanced along threading dislocations, which combined with segregation of As at the dislocations leads to severe electrical leakage. New wafers with light n-doping have been developed in collaboration with the wafer supplier Amberwave and have been shown to enable low-leakage.

c) Double quantum wells have been grown both by CVD (Princeton) and MBE (UCLA). TEM images confirm abrupt heterointerfaces between Si and SiGe layers (Fig. 2). We studied charge transfer between the wells as a function of top gate voltage. Abrupt depletion of the top layer (sharp dip in conductance and mobility) indicates inter-layer coupling between the wells.

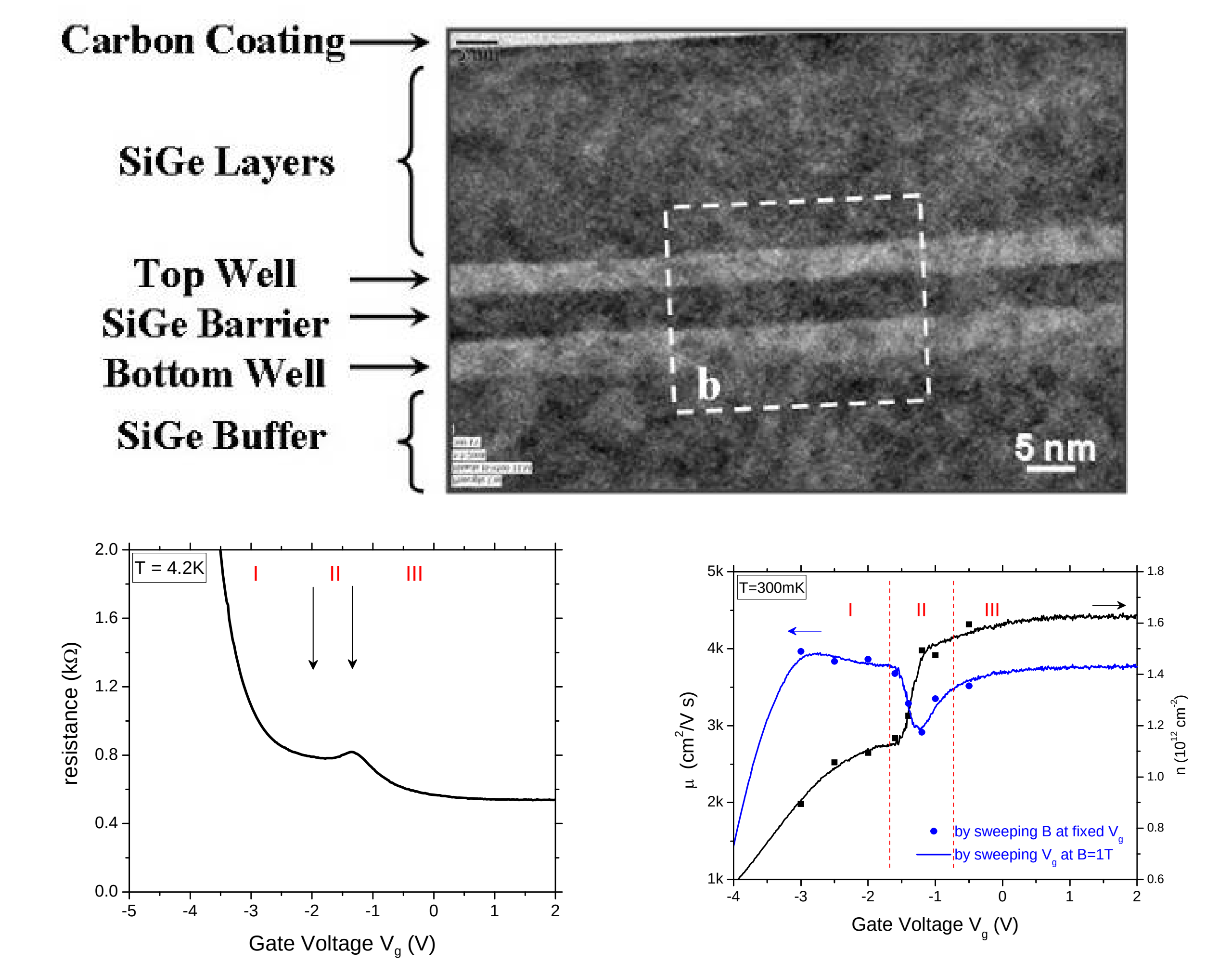

Fig 2. Top: TEM micrograph of a double quantum well heterostructure grown at Princeton. Bottom: resistance, mobility and electron density of the DQW as a function of the top gate voltage. Peak in resistance (and corresponding dip in mobility) corresponds to the depletion of the top well and transfer of the electron density into the bottom one.

d) **Epitaxially confined QD** has been demonstrated, see Fig. 3. There is very little side gate leakage (in pA range), which allows operation of all 6 gates. At low temperatures we observe Coulomb blockade oscillations. There are yet charging effects which prohibit detailed investigation of the device. In order to achieve cleaner regrowth interface we will modify the fabrication so only single crystallographic plane is exposed during regrowth.

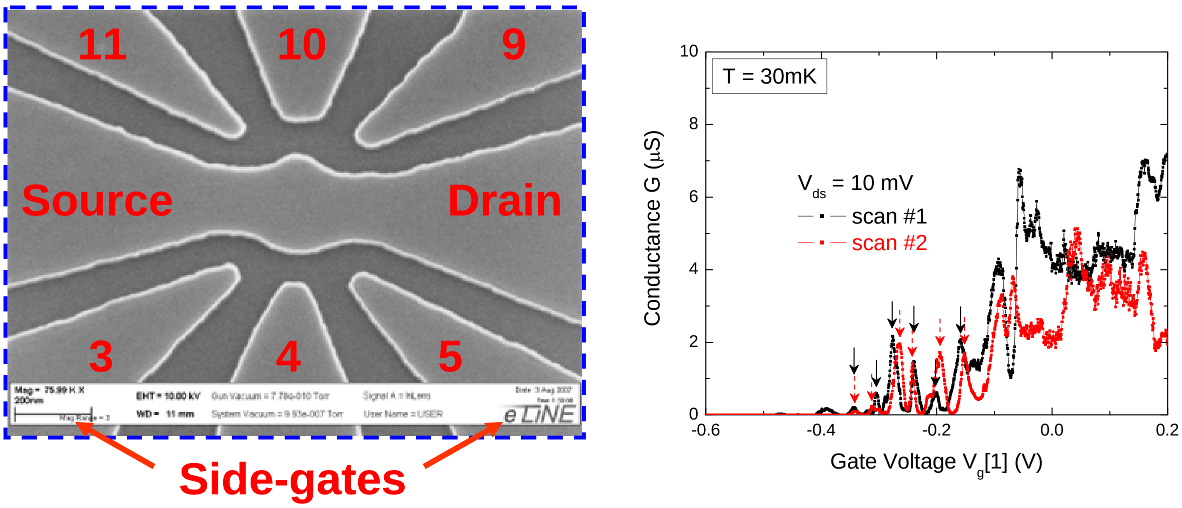

Fig. 3. SEM micrograph of a quantum dot with side gates before regrowth. Right: Coulomb blockade measured at 30 mK as a function of voltage on the plunger gates 4 and 10. The shift of CB peaks is attributed to the spurious charging effects at the interface.